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DEVELOPMENT OF A LARGE-SCALE HYDROLOGIC PREDICTION SYSTEM

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ABSTRACT

The Scripps ECPC (Experimental Climate Prediction Center) is developing an experimental off-line hydrologic prediction system for the southwestern United States. The system includes the atmospheric Global and Regional Spectral Model (GSM/RSM) and the Variable Infiltration Capacity (VIC) macro-scale hydrologic land surface model. In particular, GSM/RSM daily forecasts of precipitation, temperature (max and min), wind speed, and solar radiation are used to continuously force water and energy balance modes of the VIC model at sub-daily scales. VIC daily, weekly and monthly forecasts are made from the routine ECPC GSM/RSM forecasts for the Southwest forecasts. Daily Land Data Assimilation System (LDAS) products are used to evaluate the performance of the VIC model. As well, it shows that there are noticeable differences between the streamflow (and other hydrologic variables) forecasts and continuous simulations due to various biases in the forecast variables (especially precipitation). As long as these forecast biases are empirically corrected, useful predictions can be made.

1 INTRODUCTION

The Scripps ECPC (Experimental Climate Prediction Center) has been developing an experimental off-line hydrologic prediction system over the southwestern United States for the SAHRA (Sustainability of semi-Arid Hydrology and Riparian Areas) project. The main goal of SAHRA is to study and promote the sustainability of water resources in semi-arid regions, such as the areas over the southwestern United States (SAHRA 2002). The mission of ECPC for SAHRA is to provide a reliable long-range macro-scale hydrologic prediction over Southwest of the United States.

The hydrologic prediction system in ECPC includes the atmospheric Global and Regional Spectral Model (GSM/RSM) (Juang and Kanamitsu 1994) and the Variable Infiltration Capacity (VIC) macro-scale hydrologic land surface model (Liang et al. 1994). In particular, GSM/RSM daily forecasts of precipitation, temperature (max and min), wind speed, and solar radiation are used to continuously force water and energy balance modes of the VIC model at daily and sub-daily temporal scales. VIC daily, weekly and monthly forecasts are made from the routine ECPC GSM/RSM forecasts for the Southwest forecasts (Roads et al. 2001). Daily Land Data Assimilation System (LDAS) products (Maurer et al. 2002) from the University of Washington, Seattle, are used to validate the performance of this system. In addition, the USGS (U.S. Geological Survey) streamflow observations from the Rio Grande in New Mexico are used to study the model output.

2 BACKGROUND

GSM and RSM were developed in NMC (National Meteorological Center) and are nested models. Both of the models have identical vertical structure and physical processes except GSM with low resolution and RSM with high resolution. The component of the models is a primitive equation model on a stereographic projection and uses sine-cosine series as horizontal basis functions (Juang and Kanamitsu 1994). The physical package of the model includes longwave and shortwave radiation interactions between cloud and radiation; boundary layer processes; gravity wave drag; and enhanced topography (Roads et al. 2001). The Scripps ECPC has been making experimental, near-real-time, long-range global dynamical forecasts, and regional dynamical forecasts over the United States using GSM/RSM since 27 September 1997 (Roads et al. 2001).

The 3L-VIC (three-soil-layer VIC) model is used in the ECPC hydrologic prediction system. The VIC model is a grid-based macro-scale hydrologic model. In the model, The soil moisture content in the first two top soil layers determines the infiltration capacity and the volume of overland flow; the soil moisture in the third soil layer determines the product of the baseflow. Multiple land surface cover types are used

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in the VIC model, and the variabilities of horizontal soil moisture distribution, infiltration capacity, evapotranspiration, and overland flow are parameterized (Liang et al. 1994). Basically, there are two VIC running modes, water balance mode and energy balance mode. After assuming that the land surface soil temperature equals the near-surface air temperature, the VIC model runs on water balance mode. Using energy balance to compute the land surface temperature, the VIC model runs on energy balance mode based on water balance and energy balance of terrestrial hydrology over a study region.

3 METHODOLOGY

Figure 1 schematically shows the ECPC hydrologic prediction system. The meteorological data from the ECPC GSM/RSM output and CPC (Climate Prediction Center) observed precipitation are used to force the VIC model historical run. The weekly and seasonal forecasts of the GSM/RSM are used to force the VIC model forecast run. Overland flow and subsurface flow from the VIC simulation are routed through grid boxes and river networks using the VIC routing model (Lohmann et al. 1998). Then the simulated streamflow is compared with observed streamflow to evaluate the performance of the hydrologic prediction system.

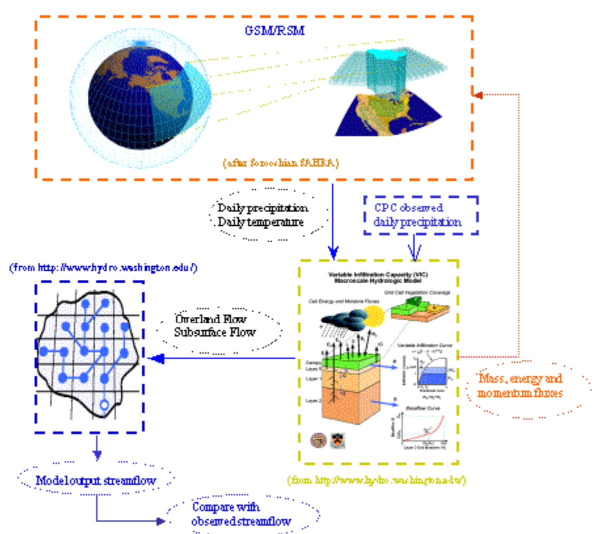

Figure 1: Schematic plot of the ECPC hydrologic prediction system.

In the ECPC hydrologic prediction system, because of the uncertain of the initial conditions and boundary conditions, and nonlinear properties of the GSM/RSM models, the system bias of the model forecast is unavoidable. To adjust the bias of the GSM/RSM meteorological forecast, the model output of the VIC historical run will be used as a benchmark of the bias adjustment, and the output of the VIC forecast run is adjusted after removing the system bias.

4 RESULTS

4.1 *Output of Hydrologic Prediction System*

The weekly prediction of various hydrologic variables over the southwestern United States from the hydrologic prediction system is made every day; the monthly prediction is made every Saturday; and the seasonal prediction is made for the first Saturday of every month. Please see URL http://ecpc.ucsd.edu/ for details of the ECPC near-real time hydrologic predictions.

4.2 *Case Study over the Rio Grande*

The Rio Grande in the US southwest is one of the longest rivers in the US and the watershed size is equal to the 11 percent of the continental United States. Most of the Rio Grande basin lies within semi-arid and arid areas (Stone et al. 1990).

The Rio Grande headwaters are in southern Colorado. The river traverses New Mexico and forms the border of the United States and Mexico. Its terminus is the Gulf of Mexico (see Fig. 2). To study the probability of streamflow prediction, five streamflow gage stations in New Mexico are chosen (see Table 1).

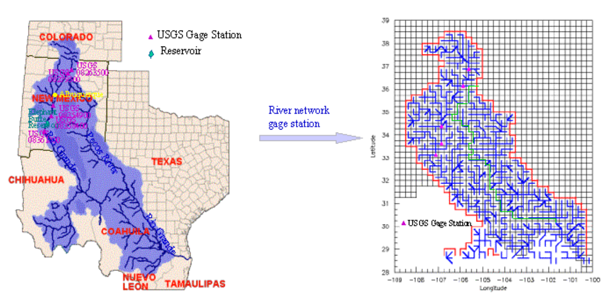

Figure 2: The location of the Rio Grande basin and its networks.

Before analyzing the outputs of hydrologic prediction system using different precipitation inputs, the one-day prediction of the GSM/RSM precipitation and CPC observed precipitation are compared. Figure 3 illustrates the area-averaged weekly GSM/RSM and CPC precipitation over the areas above the five gage stations from 1998 to 2002. It seems that the GSM/RSM output under-predicts

Table 1: Fiver gage stations, from the Rio Grande basin in New Mexico (see Fig. 2), are chosen for the study of the ECPC hydrologic prediction system.

USGS ID	Station Name	Elevation (m)	Drainage Area (km^2)
08263500	Near Cerro	2167.1	14239
08279500	Embudo	1764.5	19313
08354900	San Acacia	1418.7	62858
08358400	San Marcial	1357.9	64100
08361000	At Elephant Butte Dam	1293.0	68631

the precipitation during the summer monsoon over the Rio Grande five gage stations. However, in the Spring seasons of 1999 and 2000, GSM/RSM over-predicts the precipitation. As well, from the figure, it is clear that the precipitation in the area above the Elephant Butte Dam mainly consists with the summer monsoon rainfall and the winter snow falling.

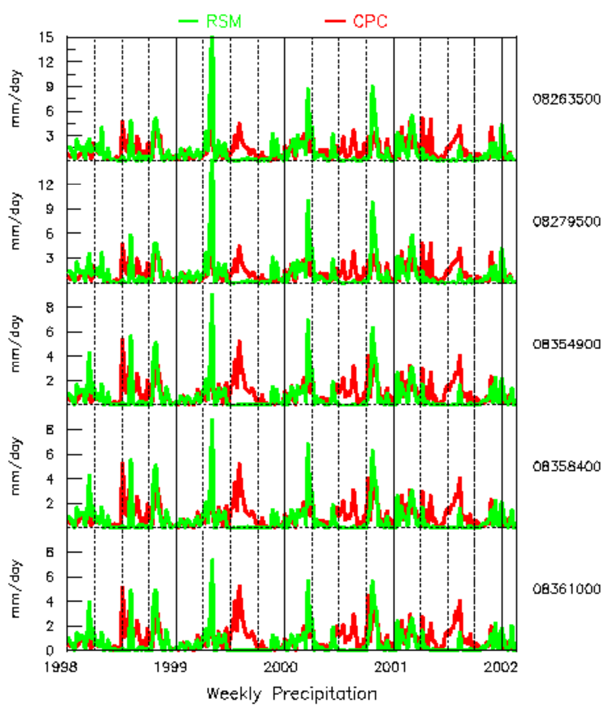

Figure 3: The comparison of the weekly RSM and CPC precipitation at the areas above the five gage stations over the Rio Grande basin.

The VIC water balance mode is used to study the hydrologic simulation over the Rio Grande. Figure 4 shows the USGS daily observed streamflow and both of the simulated streamflows from using the CPC and GSM/RSM precipitation, and the daily maximum and minimum air temperature from GSM/RSM output. The streamflow from using GSM/RSM precipitation provides much more water in the Spring season. The comparison of the USGS streamflow observations and model simulations depicts that the observations are much smaller than the simulations, especially that observations from the gage station at the Elephant Butte Dam. After investigating the human activities in the Rio Grande basin (see Stone et al. 1990), we found that the very heavy regulation has been carried out over this region since the early of the twenty century. That implies that we can not directly use the observed streamflows to validate the performance of the macro-scale land surface model. As well, it will be improper to use the observations as benchmark to adjust the products of the hydrologic prediction system.

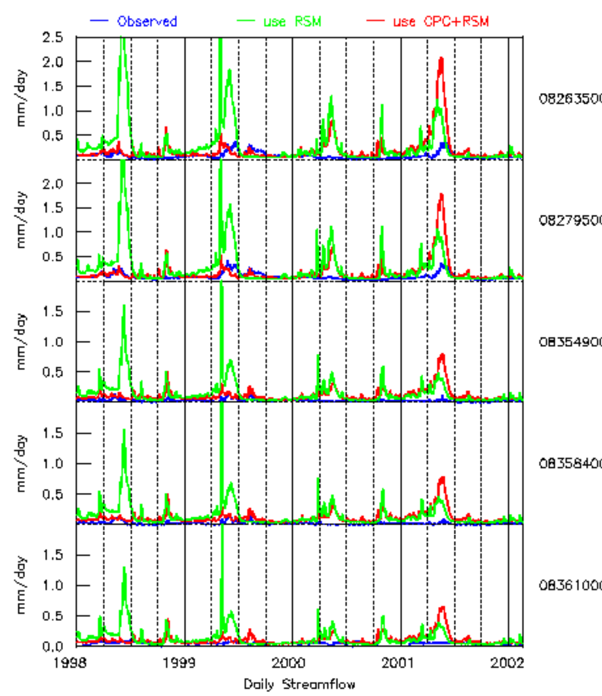

Figure 4: The comparison of model simulated daily streamflows with the USGS observations at five Rio Grande gage stations.

The above analyses corroborate that the GSM/RSM prediction includes some system bias. A useful prediction can be made only after we remove the bias from the hydrologic prediction system. However, the regulated streamflow observations can not be used to adjust the model simulations from using the GSM/RSM meteorological output. For this reason, we use the VIC historical run by using CPC precipitation as a benchmark to adjust the ECPC hydrologic predictions. Then, a seasonal streamflow prediction can be developed by using CPC precipitation to get the initial state and GSM/RSM forecast precipitation thereafter. Figure 5 shows a seasonal streamflow forecast before adjustment from the GSM/RSM forecast and the VIC model.

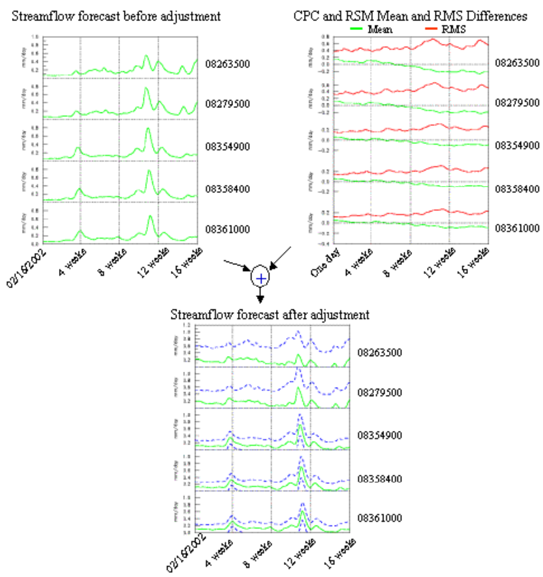

Figure 5: Adjustment of the streamflow of the GSM/RSM seasonal prediction after using the model output of CPC precipitation at five Rio Grande gage stations.

In the figure, the CPC and RSM mean difference is computed by averaging the difference of the seasonal simulated streamflows from the CPC precipitation and from the every Saturday seasonal GSM/RSM forecast from 27 September 1997 to January 2002. The RMS (root mean square) difference is the standard deviation of the difference of the simulated streamflows. That the value of the RMS increases along the length of the forecast time reflects that the magnitude of the forecast uncertainty increases along the length of the forecast time.

Combing the seasonal forecast and the CPC and RSM mean and RMS differences, we have the streamflow forecast after adjustment at five gage stations over the Rio Grande. The dash lines in the figure are the ranges of the prediction with one RMS.

4.3 *1950s Drought in Rio Grande*

Climate extremes, especially the 1950s drought, are being examined to better understand the sustainability of the Rio Grande hydrology and its riparian areas (SAHRA 2002). LDAS data from the University of Washington, Seattle, has been developed by using the VIC model, and the data covers from 1950 to 2000 (we chose the data from 1950 to 1999 for a detailed study) (Maurer et al. 2002). Therefore, we can use the LDAS data to investigate the effects of the drought on the terrestrial hydrology and to evaluate the VIC model performance over arid and semi-arid regions.

Three regions, area above the gage station near Cerro, above the gage station at Elephant Butte Dam, and the area between these two gage stations, are chosen to study the 1950s drought. Figure 6 shows the 50-year annual means of precipitation and evapotranspiration in these three regions.

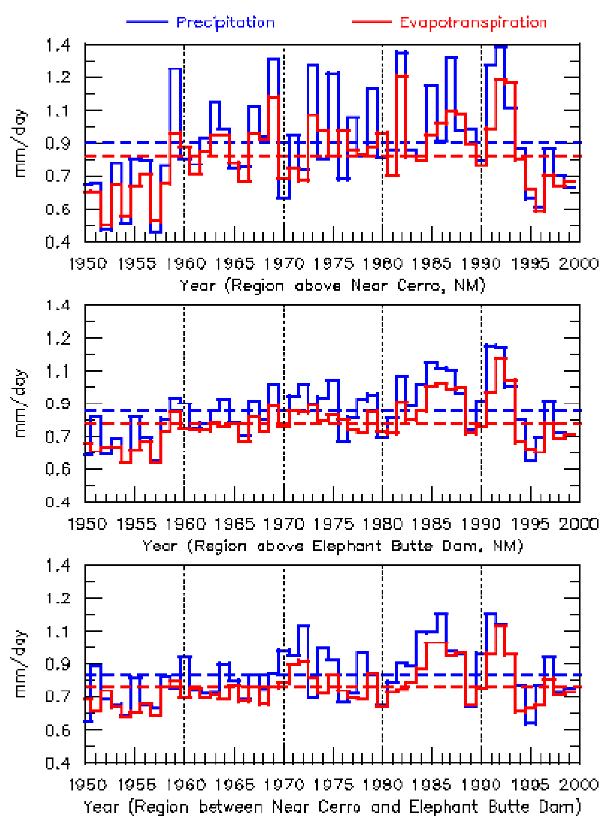

Figure 6: 50-year (1950-1999) annual means of water fluxes between the land surface and the atmosphere. Dash lines are the 50-year means of precipitation and evapotranspiration.

From the above figure, we found that the variations of the precipitation and evapotranspiration above Cerro is more significant than those between the two gage stations which also dominant the variations above the Elephant Butte Dam. In addition, the 50-year precipitation mean above Cerro is about 0.906 mm/day, and that between two gage stations is 0.847 mm/day. The evapotranspiration mean is 0.838 mm/day and 0.785 mm/day over the area above Cerro and the area between two gage stations, respectively. Consequently, the available water resources for the area above Cerro is 0.068 mm/day, and that for the area between two gage stations is 0.062 mm/day. That reflects that the area above Cerro is wetter than the area between the two gage stations.

The figure also shows that the severe drought appears in the 1950s. In the area above the gage station near Cerro, the nine-year (from 1950 to 1958) annual precipitation mean is below normal. Especially, in three years (1952, 1954 and 1957), the annual evapotranspiration mean is larger than the annual precipitation mean in this area. It means that there is no water available for the land surface during these years; in contrast, it is needed to drawing up soil moisture from soil column to support the evapotranspiration during those years. In the area between the two gage stations, the severe drought appears in six years (1950, 1952, 1953, 1954, 1956, and 1957). After checking the monthly precipitation anomaly (figure not shown here), we found that the severe drought is mainly caused by below normal precipitation during the summer monsoon time period.

5 CONCLUSIONS & FUTURE WORK

Increasing demand of water in arid and semiarid areas complicates the use of observed streamflow data to validate the performance of macroscale land surface models. The bias of GSM/RSM prediction, compared with observed precipitation, causes a phase-shifted response in hydrologic processes. Systematic adjustments are needed when using GSM/RSM data for the streamflow forecast.

The study of LDAS shows that the Rio Grande 1950s drought has significant effects on terrestrial hydrology. The simulations encompass dry and wet extremes and provide insight into the relationship between various physical processes.

In future work, we need to couple the VIC model with the GSM/RSM to examine short and long-range forecast skill for the Rio Grande and the southwestern United States.

Acknowledgments

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